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LITERATURE SEARCH INTO METHODS OF DAMPING OUT INCIPIENT TURBULENCE IN THE FLOW OF LIQUIDS (U)

Final Report

by

J. Thompsen
F. W. Boggs
N. Tokita

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ABSTRACT

The problem of delaying transition from laminar to turbulent flow has long been under investigation. This report presents a bibliography on the work that has been done for the last 40 to 50 years on this problem of transition, specifically for incompressible flow over flat plates or in pipes.

The articles included in this list are concerned with two questions: (1) What is the mechanism of transition? and (2) How can transition be delayed?

Although an extensive amount of work has been done and is still being done on the problem of delaying transition on relatively flat surfaces by means of compliant coatings, it does not appear feasible to extend this method to pipes except to a limited extent. However, recent work has indicated that the addition of non-Newtonian additives to the flow may be a promising way of delaying transition in piping systems, such as hydraulic line, normally found in industry.

It should be noted that reduction of noise in pipes is possible with the use of flexible surfaces.

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INTRODUCTION

This bibliography has been prepared as an initial step in an investigation of the possibility of constructing hydraulic lines which will maintain laminar flow at Reynolds numbers significantly higher than critical.

Since it is desired to maintain laminar flow in hydraulic lines, only articles dealing with laminar flow and its transition to turbulent flow of liquids and gases at low Mach numbers are included. In addition, since the problem of transition and flow noise are intimately related, articles concerned with flow noise in pipes are also included.

PROCEDURE

To prepare this bibliography the following plan of attack was adopted:

A. Selection of possible articles to read from a survey of technical indices and from our experience obtained working in the area of transition in boundary layer flow.

B. Choice of articles, based upon their title and abstract where obtained, which we feel are pertinent.

C. Examination and evaluation of as many of those articles as can be obtained or read at one of the public libraries in the metropolitan area.

D. Preparation of the bibliography which will include articles which were read along with their abstract and also those articles and their abstract where obtained, which limited time prevented us from reading but are pertinent to the problem.

The indices which were surveyed include:

1. Engineering Index: From 1900 - June 1963.

2. Physics Abstracts: From 1900 - June 1963.

3. Applied Mechanics Reviews: From 1948 - July 1963.

4. Journal of the Acoustical Society of America: From 1929 - July 1963.

5. Mathematical Reviews: 1962, 1961.

6. Index Medicus: 1962, 1961.

7. Technical Abstract Bulletin: 1963, 1962.

Articles pertaining to transition were obtained from the first three indices. These articles dealt both with incompressible and compressible flow in the transition range in pipes and over flat and curved surfaces. A few references dealt with flow noise in pipes. For that reason it was deemed advisable to survey the Journal of the Acoustical Society of America to insure that the literature has been adequately searched for references concerning flow noise.

Mathematical reviews for the years 1962 and 1961 were examined, but since no new references were obtained for those two years, it was felt that any further examination into the Reviews of earlier years would prove fruitless.

It was also decided to investigate the Index Medicus for references on blood flow which might be pertinent to our search. However, after examining the Index for the years 1962 and 1961, only one reference which might have bearing on the subject was discovered.

The Technical Abstract Bulletin for the years 1962 and 1962 was surveyed at the ASTIA Library in New York City. In addition, the two topics:

1. Sound and
2. Boundary layer flow

were reviewed in the card catalog. All references which could be seen were reviewed on microfilm.

From our survey of the technical indices, approximately 275 references were obtained. Many of them were not really applicable to the problem. It was decided that only references dealing with transition and flow for incompressible flow in pipes and over flat plates would be considered. From this initial list of 275 we obtained a list of 142 references which we felt were pertinent to the problem. After examining as many of these as we could at a reasonable cost, a final list of 113 references was obtained for our bibliography.

DIGEST

The literature in this summary is divided into three general classes. The largest of this is the general development of the nature of turbulence and the nature of transition. This summary of the field is given so that we have a rather complete picture of the background which led to the study of flexible surfaces in contact with fluid flow. This summary is by no means complete. It is, however, sufficiently voluminous to give an idea of the historical background and development of the boundary layer theory.

Earliest History

Transition from Laminar to turbulent flow in pipes was first observed by Reynolds[83] in 1880. It is significant to note that Reynolds early assumptions were essentially correct although it took many years for them to be adequately verified. During this early period the work of Raleigh* and others took place which led to the conclusion that at least, in the case of the flat plate, laminar flow was always stable. This seemed to be in contradiction with the conclusions which assume that turbulence resulted from the instability of the laminar flow. Our first reference is one dating to 1910 by Hopf.[34] Hopf describes the work of some of his predecessors and then measures the resistance to flow of various aqueous solutions in tubes. He shows that transition from laminar to turbulent flow appears to occur at a given Reynolds number. An interesting survey which appeared somewhat later is that by L. V. King[41] which appeared in 1916. The author gives an historical survey of the theoretical development and describes several types of fluid motion. A second part is devoted to the study of the stability of laminar flow in pipes and channels.

A later paper by Hopf[35] discusses the transition from laminar to turbulent flow. This is done on the basis of the inviscid solution of the Orr-Summerfeld equation which is shown to become increasingly stable as the Reynolds number increases. This, of course, is a paradoxical result which arises from the neglect of the asymptotic solution. It was not until some 10 years later that this problem began to be correctly treated.

In 1920 and 1921 there appeared two excellent articles by Schiller.[91,92] In his first article the author experimented with tubes purposely made rough with the object of determining whether some disturbance is necessary to initiate transition. His second article gives a systematic experimental description of the friction constant as a function of the Reynolds number. In it Schiller describes the principal features of transition, the friction constant at low Reynolds numbers following one straight line in the log plot and at higher Reynolds numbers following another. He shows the familiar sudden jump and he describes the change in the position of that jump with conditions. For example, he shows how it

* Refer to Orr (78).

occurs at high Reynolds numbers when the speed is increased and jumps back at low Reynolds number if the speed is decreased. Thus a rather complete picture, valid still today, is given of the turbulent boundary layer in a rigid tube.

In 1921 there also appeared a basic discussion of laminar and turbulent friction by von Karman.[38] In it he develops the now familiar theory for the turbulent boundary layer. He does not, however, supply an adequate theory of transition.

A major breakthrough in the understanding of this phenomenon was supplied by Heisenberg[33] in his study of stability and turbulence of fluid streams which appeared in the Annalen der Physik in 1924. Here for the first time the importance of the viscid solution of the Orr-Summerfeld equation was emphasized. For the first time it was shown that viscosity in fact is a destabilizing influence and that the viscid solution rather than the inviscid solution was the source of instability.

At the same time and shortly afterwards there appeared a number of studies of the turbulent boundary layer.[1,66,68,70,81,93] The concept of the equivalent viscosity for the Reynolds stresses appeared at this time and was discussed by several authors. It was also at this time that the concept of the mixing length was introduced by Prandtl.[79]

Development of Modern Boundary Layer Theory

In 1936 appeared the first of what might be called the modern boundary layer stability theory, that of Tollmien. Tollmien[107] recognized practically all the basic problems of the nature of transition from laminar to turbulent flow. He introduced the solution of the Orr-Summerfeld equation having a viscid solution which is asymptotic for large Reynolds numbers and an inviscid solution which is a second order differential equation. He showed how a curve of neutral stability could be plotted using this data. The plots which more modern authors obtained are quantitatively different but qualitatively have the same general aspect. The next big advance in this field was the appearance in 1945 and 1946 of a series of articles by C. C. Lin.[56] This author not only improves upon the calculations of Tollmien and Schlichting, but he discusses the logical background of the principal authors who preceded him. As a result these three articles yield a rather complete picture of the state of knowledge on boundary layer transition at the time that they were written. This was strengthened by the work of Shen.[103]

An article appeared in 1947 by Binnie and Fowler[8] which describes the effect of flow in glass tubes which contain a dilute solution of a material yielding flow birefringence. This experiment was done to illustrate transition. It is doubtful in view of the recent work on the influence of non-Newtonian additives that the conclusions drawn from these experiments are correct. However, the observations are interesting historically and the technique may prove useful in other fields.

Dryden[21] published an excellent review on the state of the science of boundary layer transition in 1947. This includes both a study of how

turbulence occurs and a description of the most recent development at that time in the theory of the turbulent boundary layer. During the same year the basic publication of Schubauer and Skramstad[100,101] appeared which verified the theory of Tollmien and Schlichting. In 1951 the first edition of Schlichting's text[96] appeared which gives a complete exposition of the boundary layer theory at that time. This textbook has been revised a number of times and has been translated into English. As a result of its frequent revisions it is at present, in new editions, free from the unfortunate errors of a trivial nature which were in the early editions.

This was the state of the science which prevailed at the time that Kramer[45] started his work in the use of compliant coatings. We will revert to this question again later. The use of compliant surfaces follows rather naturally from the theoretical background which already existed at this time.

Work on the transition both in flat plates and pipes, however, continued. There is an interesting sidelight which appeared in 1952 in an early paper discussing a non-Newtonian viscosity in a pipe. Viguier[109] is interested in the effect of the non-Newtonian term on transition. In view of the upsurge of interest in this subject at the present time, this early study is important.

In 1953 Zondek[112] showed that in plane Couette flow all modes are damped. Since this type of flow has been used as a model for the sub-layer in theories of the turbulent boundary layer in contact with flexible surfaces, this paper has important relevance to our subject.

The several years preceding 1963 have been a very active period in the study of transition. Transition in pipes has been rather less studied than transition along a flat plate. There are probably two reasons for this: first, the greater simplicity of the geometry in the flat plate which has led to a much more complete theoretical understanding of the problem, second, the important bearing that these problems have on the performance of airplane wings. We have chosen several articles as representative of the work that was being done during the last years in the study of the flat plate. This list is by no means exhaustive and the total number of significant papers is many times this size. However, they do give a fair idea of the type of work that was done. The outstanding accomplishment of this type is probably a better understanding of the detailed process which takes place when transition occurs. It has been possible, for example, to divide the transition region into three characteristic areas. When the Reynolds number is only slightly above the instability Reynolds number, a condition exists where Tollmein-Schlichting waves are slightly amplified and the boundary layer can be properly represented by superposition of these waves along the unperturbed boundary.[86,87,90] When the Reynolds number is somewhat larger than this, nonlinear effects become important and random uncorrelated fluctuations begin to appear. The third region for still higher Reynolds number takes on the general appearance of turbulent fluctuations.

Another important aspect which has been studied in detail by Benny and Lin[5] are the non-linear effects from the theoretical point of view. This type of work has been further studied experimentally by Schubauer,[99]

his associates and others[23,102] who have described in detail the process of transition and the characteristic bursts of turbulence which mark transition. Similar observations have been made in pipes.[18,69,104]

The bursts of turbulence which characterize transition regions have been observed in a number of ways which tend to confirm this general picture. There have also been studies of transverse contamination by turbulence.[19] At the same time a number of review articles[73,94,95] have appeared as well as some books. Notably the work of Lin[57] on stability and Batchelor's[2] book on turbulence. There is a group of papers which were presented at the International Union of Theoretical and Applied Mechanics at Freiburg which has appeared in book form. This is an excellent source of material on this subject.[27,28]

There are a number of papers by Lindgren[59-65] on transition in pipes. Of particular interest are his observations of the effect of bentonite as an additive to water.

It is apparent at the present time that the details of transition are exceedingly complex and that the theoretical developments are unable to keep pace with experimental knowledge. Indeed, there is some question as to whether the complex phenomena which characterize the turbulent boundary layer can ever be adequately studied theoretically. It is almost universally agreed that these processes are both essentially non-linear and three dimensional.

Effect of Flexible Surfaces on Boundary Layer

Since it has been known for many years that turbulent fluctuations are accompanied by pressure fluctuations, it is perhaps surprising that interest in the interaction between pressure fluctuations in the fluid and a flexible wall were so long delayed. Although there is an early paper on the subject of flow in flexible tubes, the author was primarily interested in the influence of curvature[24] on the flow. Some further work has appeared from time to time in the literature on blood circulation, primarily concerned with the influence of the flexible wall on pressure pulses.[39] Associated with this there have been a number of papers on the transmission of sound through pipes with flexible walls. We have been able to find no reference to the interaction between the pressure fluctuations of turbulence or transition and a flexible surface for the incompressible fluid before the publication of Max O. Kramer in 1957.[45] Kramer was interested in the possibility of delaying transition along a flat plate with the hope of producing lower drag. Kramer published a series of papers [46,48] and patents[49] on this subject in which he was able to observe drag reduction on a towed underwater body. He reports drag reductions of as much as 50% and he attributes the paradoxically high speed observed on dolphins[47,29,54] to this same type of effect. In addition there are patents on the effect of solid rubber by Boggs.[10,11,12] This work was rapidly followed by a number of theoretical treatments on the subject. The first of these to appear was that of Betchov.[7] Betchov's discussion is contained in an article concerned with a simplified picture of transition. He concludes that delayed transition by flexible surfaces is possible. A somewhat similar treatment which follows very closely the Tollmien-Schlichting treatment of the boundary layer was published by Boggs and Tokita[15] in 1960. Both of these discussions neglect the product of the

slope of the unperturbed velocity by the perturbed velocity. This is not justified in the stability analysis and the first correct treatment which was done by Benjamin[4] appeared in 1960. The conclusion of this discussion is that delayed transition is possible on the flat plate at zero incidence. Benjamin shows conclusively that, contrary to the assumptions that Kramer originally made, the delayed transition is not due to damping in the coating but rather to the compliance. It is desirable according to his treatment to reduce the damping to a minimum. This is in accord with observations which were made by Kramer. Benjamin also points out the presence of other types of instability which he refers to as B waves.

A paper by Landahl[53] examines the energetics of the Tollmien-Schlichting waves and shows that the condition of waviness is actually one of lower energy, hence energy tends to be fed into the wave. It is this aspect of the problem which leads to the destabilizing effect of loss in the boundary layer.

At the same time as this work was in progress, further experimental work was carried out. Boggs and Frey[13] and Frey and Holtermann[25] made measurements on the drag of small planing hulls. They were able to show that drag reduction was maximum for a relatively small Reynolds number and then decreased with increasing wetted length. This is in accord with the theoretical conclusions that were made early that transition would always occur at some Reynolds number although it might be delayed.

Observations made on towed underwater bodies at the David Taylor Model Basin showed the presence of static divergence.[14,82] This is a type of instability different from the B waves of Benjamin and associated with the flexibility of the surface.

A later report by Boggs and Tokita[16] discusses not only delayed transition but the various types of instability which are associated with flexible surfaces. It shows that the B waves of Benjamin are closely related to Kelvin-Helmholtz instability and that any benefits derivable from delayed transition will be severely limited by the other types of instability which may occur. Indeed, they show that on certain types of surface the greatest delay in transition will occur at velocities just below those leading to instability.

The problem of noise generation is always associated with the problem of turbulence.[22] There have been a number of papers on the propagation of sound in pipes. Liquid filled pipes are found to display all the characteristics of a wave guide. When the pipe is very rigid and shows little loss, the characteristics of the propagating wave in the pipe depend only on its dimensions and on the nature of the liquid. In the case of flexible walls, a number of types of behavior occur depending upon the nature of the walls. Jacobi[30] gives a discussion of many of these points. A somewhat later analysis by Morgan and Kiley[72] relates the propagation characteristics in the fluid to the characteristics of the pipe. Further work by Morgan and Ferrante[71] extend this work to the case where there is flow superimposed on the sound wave. In this case the behavior is not the same in both directions. The authors assume that laminar flow exists. They do not consider the more important case of fully developed turbulence.

Junger[37] gives us a study of the mode of propagation in a fluid filled pipe having a massive wall and which is operating above the resonance frequency of the ring type mode. Work has appeared on the pressure effect in elastic tubes in association with the circulation of the blood.[39] There is an interesting paper on the interaction between rigid wavy walls and the flow in pipes.[52]

More important than all, however, for our purpose is a report by Smith[105] describing his measurement of flow resistance in flexible walled pipes. Smith measured the flow resistance of pipes lined with gelatin to the flow of a hydrocarbon fluid. All his data showed either no decrease in drag or a slight increase. It seems probable that all his results are associated with turbulent flow. The increased drag is probably associated with static divergence of the flexible wall. The results tend to show that in the case of turbulent flow, at least, flexible surfaces can have no beneficial effect as far as drag is concerned. These results are confirmed by measurements of Lumley[67] and his associates in the water tunnel at the Ordnance Research Laboratory. They are further confirmed by recent work by Schubauer.[98]

General Discussion

Although several measurements of drag reduction have been made when flexible surfaces were used, there have been no observations which confirm the hypothesis of delayed transition. Furthermore the drag experiments have been notably difficult to repeat exactly, the values obtained at later dates being in some cases markedly different from the earlier results. Kramer attributed these variations to the effect of ambient turbulence and this explanation may be correct. An alternative explanation is the sensitivity of the rubber coatings used to temperature. A third is the possibility of gradual damage to the coatings through excitation of other types of instability. Since the largest possible effect of delayed transition occurs when the surface is close to static divergence, drag reduction will be greatest when the coating is sensitive to external pressure fluctuations. It seems entirely possible that some of the coatings may have been so damaged.

In the case of pipe, it has not been established whether delayed transition is possible or not. Work at Boeing[30,31] on plane Poiseuille flow tends to show the possibility of transition delay. Whether plane Poiseuille flow is an adequate representation of Poiseuille flow in a pipe is open to some question. A further difficulty with pipe arises from the fact that if delayed transition is the only possible mechanism of reduced drag, as is the case on the flat plate, only a limited amount of delay may be obtained. The benefits achieved through lining pipe might be quite small. Certainly there do not seem to exist the prospects of substantial reduction in drag by simple means that seem to be possible through the use of non-Newtonian additives. A more complete examination of this problem would, however, seem to be justified since not only the possibility of reduced fluid flow is possible, but also the reduction in noise.

ABSTRACTS OF LITERATURE REFERENCES

(All literature references listed below have been read except those marked with an asterisk *)

1. Baubiac, J.: Transient Regimes in the Motion of Liquids and the Establishment of Turbulent Flow. Comptes Rendus (Paris), Vol. 198, 148-51 (1934)

   Study of the variation of the rate of flow of liquids in tubes at various Reynolds Number shows that there is a transient regime bordering upon the turbulent. The establishment of the turbulent regime is found to be increasingly rapid as the Reynolds Number increases.

2. Batchelor, G. K.: Theory of Homogeneous Turbulence, Cambridge University Press, 1956

   This book gives a complete discussion of the statistical theory of homogeneous turbulence as it existed in 1956. It is an ideal source of information on this subject.

* 3. Belyakova, V. K.: On the Stability of Flow of a Viscous Fluid in a Straight Round Pipe. Prikl. Mat. Mekh., Vol. 14, 105-110 (1950)

   Author presents solution of the non-linear differential equation for viscous flow in round tube. The linearization is obtained by method of small perturbation. A new set of boundary conditions (different from those used by Th. Sexl, Germany, 1927 is introduced and the stability parameters are introduced.

4. Benjamin, T. B.: Effects of Flexible Boundary on Hydrodynamic Stability. Jrnl. of Fluid Mechs., Vol. 9, 513-32 (1960)

   Stability problem for flow past flexible boundary is formulated in general wave which allows full exploration of possibility of stabilizing effect without need to assign specific properties to flexible medium. The author concludes that stabilization is possible. He also shows that B waves, a form of Kelvin-Helmholtz instability are possible.

5. Benny, D. J., Lin, C. C.: On the Secondary Motion Induced by Oscillations in a Shear Flow. Phys. of Fluids, Vol. 3 (1960)

   The authors present a theoretical discussion on the influence of second order terms in the oscillation on stability of shear flow. The combined effect of the primary and secondary oscillations yield a net motion similar to that observed by Schubauer, Klehanoff & Tidstrom.

6. Betchov, R.: Simplified Analysis of Boundary Layer Oscillation. Report No. E 29174, Douglas Aircraft Co., El Segundo, Calif., Mar. 15, 1959

7. Betchov, R.: On the Mechanism of Turbulent Transition. Phys. of Fluids, Vol. 3, 1026-27 (1960)

A simple model of secondary instability which may be related to the process of turbulent transition is discussed by the author. It contains a brief treatment of flexible surfaces.

8. Binnie, A. M., Fowler, J. S.: A Study by a Double-Refraction Method of the Development of Turbulence in a Long Circular Tube. Proc. Roy. Soc. Series A, Vol. 192, 32-44, (1947)

A streaming double-refraction method was employed to examine the flow in a long glass tube of a very weak solution of benzopurpurin in water. Two kinds of turbulent entry were used: with one, laminar flow at a Reynolds Number of about 1900 was observed at cross-sections more than 120 dia. from the entry; with the other the corresponding distance was 90 dia. The nature of the breakdown of laminar flow at a cross-section was found to depend upon the kind of entry and upon the distance of the cross-section from the inlet.

9. Blasius, H.: Grenzchichten in Flussigkeiten mit Kleiner Reibung, Z. Math. U. Phys., Vol. 56, 1 (1908)

10. Boggs, F. W.: U. S. Patent #2,971,301

This patent relates to the method of making a liquid-filled drag reducing covering for a body moving completely immersed in fluid.

11. Boggs, F. W.: U. S. Patent #3,051,599, June 23, 1958

This invention relates to improvements in the method of reducing the frictional drag on an object moving in a fluid medium wherein turbulence in the boundary layer between the object and the medium is reduced by applying to the surface of the object a thin flexible, resilient covering or coating having certain characteristics.

12. Boggs, F. W.: U. S. Patent #3,076,725, February 5, 1963

This invention relates to a method of reducing the frictional drag on an object moving in a fluid medium. It is specifically directed to a method for damping out turbulence along the object's fluid-contacting surfaces and thus maintaining laminar boundary layer flow under conditions where turbulent boundary layer flow would otherwise prevail.

13. Boggs, F. W., Frey, H. R.: The Effect of a Lamiflo Coating on a Small Planing Hull Having Zero Deadrise, U. S. Rubber Report, June, 1961

14. Boggs, F. W., Frey, H. R., Hahn, E. R.: Construction and Testing of Coating for Drag Reduction, Final Report, Department of the Navy Contract Now-60-0227-C February, 1962

This report describes the construction and testing of constant pressure bodies covered with compliant coatings. The models were found to be deffective and the results are therefore inconclusive. It gives the first observations of static divergence of the surface.

15. Boggs, F. W., Tokita, N.: A Theory of Stability of Laminar Flow Along Compliant Plates. Third Symposium on Naval Hydrodynamics, September 19-22, 1960, Schereningen (The Hague), Netherlands

16. Boggs, F. W., Tokita, N.: Hydroelastic Behavior of Compliant Coatings. Partial Fulfillment of Department of Navy, Bureau of Weapons Contract Now-60-06760C (1963)

17. Camichel, C.: Transitory Regimes. Comptes Rendus (Paris) Vol. 195, 1200-02, (1932)

The work of Crausse & Baubiac on phenomena characterizing the period of establishment of the steady state of liquid flow in a cylindrical tube and past a circular obstacle and the work of the author together with Escande & Dupin relating to the establishment of vortex motion are briefly referred to.

18. Carstens, M. R.: Transition from Laminar to Turbulent Flow in Pipe. ASCE Proc. (J. Hydr. Div.), Vol. 83, 30 pg. (1957)

Author concludes, based upon his experiments, that 1) turbulence originated as spots, 2) downstream face of turbulent spots was transported with centerline velocity of preceding laminar flow, 3) turbulent spot formation was in qualitative agreement with Tollmein-Schlichting theory of small disturbences.

19. Charters, A. C.: Transition Between Laminar and Turbulent Flow by Transverse Contamination. NACA TN #891 (1943)

The author concludes that transition can be caused by a transverse contamination; i.e., a mechanism exists by which boundary layer transition can transport itself laterally across a surface. This later spread took place at an approximately constant rate, which varied slowly with the velocity of the main flow but which, once transition started, was independent of the originating cause.

20. Dhawan, N.: Some Properties of Boundary Layer Flow During the Transition from Laminar to Turbulent Motion. J. Fluid Mech., Vol. 3, 418-436 (1958)

The author examines transition in the boundary layer on a flat plate from the point of view of intermittent production of turbulent spots. He shows that the transition Reynolds Number is functionally related to the instability Reynolds Number in the following manner:

$$Re_{inst.} = \alpha \, Re_{trans.}^{\beta} \quad \text{where } \alpha \approx 5, \ \beta \approx 8$$

21. Dryden, H. L.: Some Recent Contributions to Study of Transition and Turbulent Boundary Layers. NACA TN #1168, 32 pg., (1947)

Review of present state of problem of instability of laminar boundary layer and methods being used for fundamental studies of turbulent fluctuations in turbulent boundary layer.

*22. Dyer, I.: Boundary Layer Induced Flow Noise. Jl. of the Acous. Soc. of Amer. 58th Meeting, Session C, October 22-24, 1959

A discussion is given on the magnitude of flow noise in underwater devices associated with turbulent boundary layer.

23. Elder, J. W.: An Experimental Investigation of Turbulent Spots and Breakdown to Turbulence. J. Fluid Mech., Vol. 9, 235-46 (1960)

The theory of hydrodynamic stability and the impact on it of recent work with turbulent spots is discussed. Emmon's (1951) assumptions about the growth and interaction of turbulent spots are found experimentally to be substantially correct. In particular it is shown that the region of turbulent flow on a flat plate is simply the sum of the areas that would be obtained if all spots grew independently.

24. Eustice, J.: Flow of Water in Curved Pipes. Roy. Soc. Proc. Series A, Vol. 84, 107-118 (1910)

Author wanted to study effect of curvature of the flow tube on the flow of water. Tests were made using flexible pressure tubing which were a composite of rubber and canvas.

25. Frey, H. R., Holtermann, T. J.: The Effect of Lamiflo Coatings on a Small Warped Hull. U. S. Rubber Report

26. Gibson, H. H.: Breakdown of Streamline Motion at the Higher Critical Velocity in Pipes of Circular Cross-Section. Phil. Mag., Vol. 15, 637-647 (1933)

Discussion of the phenomena of critical velocity suggests that breakdown is related to the rate of variation of energy across a diameter of the pipe. Author determines at what radius of a pipe breakdown of laminar to turbulent flow first occurs.

27. Görtler, H.: Dreidimensionale Instabilitäte der ebenin Staupunkt Strömung gegenüber wirbelartigen Storungen. Vieweg & Sohn (Bransschweig, Germany) (1955)

This gives a series of articles on the basic boundary layer theory. This is an excellent source of general information.

28. Görtler, H.: Editor; Symposium on Boundary Layer Research. International Union of Theoretical & Applied Mechanics, Freiburg, Germany (1957)

Article by Schubauer gives some recent data on the initiation of turbulence. He shows that turbulence begins thru the formation of turbulent spots.

An article by C. C. Lin describes the basic theory of turbulence including a discussion of the non-linear term in the perturbation of the Navier-Stokes Eq.

29. Gray, J.: How Fishes Swim. Sci. Am., Vol. 197, 48-54 (Aug. 1957)

Author introduces the problem of relating the expected muscle power of dolphins to the speeds which they are supposed to be capable of attaining.

30. Hains, F. D., Price, J. F.: Stability of Plane Poiseuille Flow Between Flexible Walls. Boeing Scientific Research Laboratories Flight Sciences Laboratory Report No. 37, February, 1961

The stability of small disturbences is considered for plane Poiseuille flow between flexible walls which are assumed to be thin stretched membranes resting on an elastic foundation with viscous damping. Solution for the eigen values of the Orr-Sommerfeld equation for these boundary conditions is obtained numerically by a finite difference technique. The stability curves for several values of the wall coefficient are presented. The variation of the critical Reynolds Number is found only for the two special cases where the wall has damping only or tension only.

The conditions for instability of the wall itself are derived for the case of zero damping.

31. Hains, F. D., Price, J. F.: Further Remarks on the Stability of Plane Poiseuille Flow Between Flexible Walls. Boeing Scientific Research Laboratories Flight Sciences Laboratory Report No. 53, December 1961

This report is an extension of the problem the authors presented in their report of February 1961.

32. Hanks, R. W.: Laminar-Turbulent Transition for Flow in Pipes, Concentric Annuli & Parallel Plates. A.I.Ch.E. Jl. Vol. 9, 45-48 (1963)

The author is concerned with obtaining a more universal criterion of stability which can be used to define the stability condition in pipes of unusual shape or for non-Newtonian fluids.

33. Heisenberg, W.: Stability and Turbulence of Fluid Streams. Ann. der Physik, Vol. 74, 577-627 (1924)

This gives Heisenbergs discussion of the stability of the Orr-Sommerfeld Eq. It is the first discussion which points out the importance of the viscous term.

34. Hopf, L.: Turbulence in Liquid Stream. Ann. der Physik, Vol. 32, 777-808 (1910)

Article describes measurements of the resistance to flow of various aqueous solutions in tubes. The transition to turbulent flow at a given Reynolds Number seems to verified.

35. Hopf, L.: On the Theory of Turbulence. Ann. der Physik, Vol. 59, 538-582 (1919)

This author points out that the inviscid solution which is stable becomes increasingly valid as the Reynolds Number increases. This of course arrives from the incorrect method of obtaining the solution by considering only the inviscid approximation.

36. Jacobi, W. J.: Propagation of Sound Waves in Liquid Filled Tubes. Jl. of the Acous. Soc. of Amer., Vol. 21, 120-127 (1948)

A theoretical and experimental treatment is given of guided sound wave transmission along circular cylinders of ideal liquid with various non-dissipative boundary conditions.

37. Junger, M. C.: Sound Progagation in Fluid-Filled Tubes with Massive Wall Reactance. Jl. of the Acous. Soc. Amer., Vol. 28, 165-67 (1956)

Author presents results of an experimental study of the zero order mode of propagation in a fluid-filled tube having a massive wall reactance. The observed and theoretical dispersion curves, which show good agreement, display a high-path cut-off frequency. There is a dead zone between the frequency and the ring resonnance frequency of the tube.

38. vonKarman, T.: Laminar and Turbulent Friction. Zeit. fur angewandte Mathematik U. Mechanik, Vol. 1, 233-252 (1921)

This is the theory for the turbulent boundary layer and of the laminar boundary layer. This is widely discussed in texts.

39. Kenner, T.: Transformation of Pressure Waves in the Elastic Tube. Z. Kreislaufforsch, Vol. 49, 887-90 (1960)

40. King, A. L.: Flow of Fluids with Non-uniform Viscosity in Tubes with Distensible Walls (Blood Flow). Am. Phys. Soc. Proc. June, 1945

Three factors influence the rate of blood flow thru a blood vessel; 1) the non-uniformity of plasmol viscosity, 2) the elasticity of the vessel wall and 3) the presence of erythrocytes and other corpuscles.

41. King, L. V.: Theory and Experiments Relating to the Establishment of Turbulent Flow in Pipes and Channels. Phil. Mag., Vol. 31, 322-338 (1916)

This paper is divided into two parts. The first part deals in 4 sections with the mathematical theory of viscosity and its experimental verification. Part two deals in 2 sections with the stability of laminar flow in pipes and channels.

*42. Klebanoff, P. S., Tidstrom, K. D.: Evolution of Amplified Waves Leading to Transition in Boundary Layer with Zero Pressure Gradient, NASA TN #D-195, 67 pg., (1959)

As a result of their investigations of instability of laminar boundary layer leading to transition, the authors conclude that motions leading to transition are strongly three-dimensional.

43. Klebanoff, P. S., Tidstrom, K.D., Sargent, L.M.: Three-Dimensional Nature of Boundary Layer Instability. J. Fluid Mech., Vol. 12, 1-34 (1962)

The authors show that transition is essentially three-dimensional and non-linear in character.

44. Kovasznay, L. S. G., Komoda, H., Vasudeva, V.: Detailed Flow Field in Transition. Proc. Heat Transfer, Fluid Mech. Inst., Seattle, Wash.: Stanford, Calif., Stanford Univ. Press. (1-26), (1962)

The breakdown of the laminar boundary layer on a flat plate with zero pressure gradient was studied using a 10 channel linearized d.c. coupled hot-wire system. The detailed instantaneous flow field was mapped out in the breakdown phase of a three-dimensional excited laminar instability wave. The development of the flow field was followed from the conventional Tollmien-Schlichting waves into the "one spike" and "two spike" stage in a detailed and quantitative manner.

45. Kramer, M. O.: Boundary Layer Stabilization by Distributed Damping. Journal Aero. Sciences, Vol. 4, No. 6 (1957).

This gives a brief description of Kramer's early work. He measures the drag on a drum rotating in water. The drag on a drum covered with a flexible surface is compared to the drag on a rigid drum.

46. Kramer, M. O.: Boundary Layer Stabilization by Distributed Damping. Am. Soc. of Naval Engrs. Jl., Vol. 72, 25-30 (1960)

Presents method for retaining stable or laminar boundary layer over entire wetted surface of high speed bodies and profiles. Gives theory of distributed damping for ducted coatings. Gives results of marine tests on ducted coating used on towed bodies, which consists of heavy rubber diaphragm supported by multitude of tiny rubber stubs with viscous fluid in spaces.

47. Kramer, M. O.: Dolphin's Secret. Am. Soc. Naval Engrs. Jl., Vol. 73, 103-107 (1961)

Gives Kramer's observations on Dolphins and his subsequent experiments which he conducted to imitate the skin of a dolphin in order to develop fully laminar flow on bodies towed under water.

48. Kramer, M. O.: Boundary Layer Stabilization by Distributed Damping. Naval Engrs. Jl., Vol. 74, 341-48 (1962)

Similar to author's report in 1960. Adds some more experimental results.

49. Kramer, M. O.: Canadian Patent No. 641,268 - Also Australian, Belgium, French, Italian and Japanese patents covering same material. United States patent pending.

This is the basic patent on the use of flexible coatings to reduce fluid drag. It describes the principle in elementary terms and describes several possible embodiments of the idea.

50. Kuethe, A. M., Lin, C. C.: Jl. of Aero. Sci., Vol. 23, 401-516 (1956)

This anniversary issue commemorating the 75th birthday of Th. vonKarman contains two articles relevant to the process of transition. One is by Kuethe and the other by Lin. The former discusses the transition in pipes and the second is concerned with the turbulent boundary.

*51. Kuethe, A. M., and Raman: Some Details of the Transition to Turbulent Flow in Poiseuille Flow in a Tube. AFOSR TR 59-84 (U. of Mich., Dept. of Aero. & Astro. Eng.) 31 pgs. (1959)

Measurements of velocity fluctuations, Reynolds stresses and shearing stresses at the wall in the transition region of a tube are presented.

52. Laird, A. D. K., Brunner, R. K., Haughton, K. E.: Laminar-Turbulent Transition in Waved Tubes. ASCE - Proc., Vol. 88, nHYI, 1-8 (1962)

Paper presents test results and explains effects of tube flexibility, oscillations of tube walls and shape of wall. Deals especially with effects of wavelength of wave shaped wall of glass tubing.

53. Landahl, M. T.: On Stability of Laminar Incompressible Boundary Layer over Flexible Surface. Jl. of Fluid Mechs., Vol. 13, 609-32 (1962)

Complete physical explanation for influence of infinite flexible wall on boundary layer stability. Numerical examples show that increases in critical Reynolds Number that can be achieved with wall of moderate flexibility is modest and that some other explanation for experimentally observed effects of flexible wall on friction drag must be considered.

54. Lang, T. G., Daybell, D. A.: Porpoise Performance Tests in a Sea-Water Tank. NAVWEPS Report #8060, 51 pg. (1963)

This report deals with a series of tests-consisting of measurements of top speed, horsepower output and drag coefficient-made to determine how a porpoise's power compares with that of other mammals, and how its hydrodynamic characteristics compare with those of conventional man-made submerged bodies.

55. Langhaar, H. L.: Steady Flow in the Transition Length of a Straight Tube. J. Appl. Mech., ASME Trans., Vol. 64, A55-A58 (1942)

By means of a linearizing approximation, the Navier-Stokes equations are solved for the case of steady flow in the transition length of a straight tube. The parameter of the family of velocity profiles obtained is tabulated against the axial coordinate in a dimensionless form. Hence the length of transition is obtained.

56. Lin, C. C.: On the Stability of Two-Dimensional Parallel Flows; Parts I, II, III. Quart. Appl. Math., Vol. 3, I-117-142, II-218-234, III-277-301 (1946)

Presents a historical survey of the existing theories of the transition from steady to turbulent flow. A critical survey of the work of Raleigh and Tollmien is made for stability in both an inviscid and viscous fluid. The author also develops his own concepts for the theoretical calculation of transition.

57. Lin, C. C.: The Theory of Hydrodynamic Stability, Cambridge (1955)

This book gives a rather complete treatment of the theory of hydrodynamic stability. It leans heavily on Lin's work. It is an extension of the three articles previously discussed.

58. Lindgren, E. R.: Note on Flow of Liwuids in Tubes. Applied Soc. Research, Sec. A., Vol. 4, 313-16 (1954)

In previous work,* it had been shown that generally accepted ideas concerning transition between laminar and turbulent fluid motion in smooth pipes are very probably erroneous; illustration of this is given and further observations reported; concept of laminar sub-layer as special part of turbulent boundary layer is questioned.

* Lindgren, E. R.: Ark. Fys. 7, no. 23 (1953)

59. Lindgren, E. R.: Liquid Flow in Tubes. I-The Transition Process Under Highly Distrubed Entrance Flow. Ark. Fys, Vol. 15, 97-119 (1959)

Some peculiar features of the stream-birefringent effects of White Hector bentonitc suspensions in tube flow have been discovered and are briefly discussed.

The significance of the fact that disturbances emanating from the tube inlet have a considerably longer time of decay than eddies generated by turbulent flash bodies is discussed and appears to have a bearing on the vortex strength of turbulent flash bodies.

An examination of the characteristic features of the turbulent flashes confirms that the turbulent eddies are produced within wall-near layers from where they diffuse into central parts of the flow where dissipation takes place. There are some characteristic mass transfer and velocity distribution patterns which appear to play an important role in the maintenance processes of the turbulent flashes.

60. Lindgren, E. R.: Liquid Flow in Tubes.II-The Transition Process under Less Disturbed Inlet Flow Conditions. Ark. Fys, Vol. 15, 503-19 (1959)

Findings in Part I are confirmed, according to which transition is caused by primary inlet disturbances of finite strength which cause the initiation of turbulent spots before they fade away and according to which the spots during their downstream travel develop into turbulent slugs.

61. Lindgren, E. R.: Liquid Flow in Tubes. III-Characteristic Data of the Transition Process. Ark. Fys., Vol. 16, 101-12 (1959)

Experimental evidence is presented which indicates that the transition process depends on some properties of the liquids which are not accounted for by the coefficient of viscosity and the density. The findings actually demonstrate that the Reynolds law of similarity does not entirely apply to the flows investigated.

62. Lindgren, E. R.: Liquid Flow in Tubes. IV-The Transition Process and Turbulent Flow Related to Tube Diameter and Microscopic Surface Properties. Ark. Fys., Vol. 18, 449-64 (1960)

Studies previously reported on the transition process have been carried further by variation of tube diameter and surface finish. It has been found that these variations affect certain transition quantities.

Author concludes that the transition process and turbulence maintenance mechanism involve a complicated pattern of factors which at present cannot be separated from one another.

63. Lindgren, E. R.: Liquid Flow in Tubes. V-Effects of Lateral Tube Deflections on Some Turbulent Transition Quantities. Ark. Fys. Vol. 18, 533-41 (1960)

The present observations indicate that rather slight lateral tube deflections may influence the transition pattern, causing the burst and development of turbulent slugs in primarily undisturbed laminar flow at high Reynolds Number, while simultaneously a distinct damping effect is noted on the rate of development of already existing turbulent streaks when compared with their rate of extension in straight tube flow.

64. Lindgren, E. R.: Liquid Flow in Tubes. VI-Viscosity Data on Flows of Distilled Water Through Cylinderical Pipes. Ark. Fys., Vol. 22 503-15 (1962)

A report is made of pressure drop measurements on flows of distilled water thru cylindrical plexiglass pipes. The experiments indicate a systematic increase of the absolute viscosity values with increasing tube diameter.

65. Lindgren, E. R.: Liquid Flow in Tubes. VII-Momentum Perturbation and Breakdown of Steady Flow in Relation to Wall Roughness. Ark. Fys., Vol. 23, 403-9 (1962)

Experiments show that breakdown of laminar pipe flow is not uniquely correlated to the amount of disturbance momentum imposed on the flow, within the refinement of the present experimental technique, nor does the breakdown in any way seem to be dependent on the surface properties of the tube walls in the case of close packed, evenly distributed roughness elements even when they are rather large.

66. Lorenz, H.: Critical Flow Velocity in a Circular Tube. Phys. Zeits, Vol. 27, 533-36 (1926)

This paper with a previous one by the same author* gives a theoretical discussion of the turbulent flow in pipes in which he describes a boundary layer like flow near the wall and an average flow in the center of the pipe. He finds good agreement with the experimental results of Schiller.

* Lorenz, H.: The Turbulence Problem for the Straight Circular Pipe. Phys. Zeits., Vol. 26, 557-563 (1925)

67. Lumley, J. L.: Personal communication

68. Maccoll, J. W.: Modern Aerodynamical Research in Germany. Royal Aero. Soc. Jl., Vol. 34, 649-689 (1930)

Paper deals with the 3 regions of fluid flow: 1) Laminar 2) Transition and 3) Turbulent. It considers flow over flat plates, thru pipes & thru channels. Most of this material is similar to that found in Schlicting's text, Boundary Layer Theory.

69. Mattioli, E., Zito, G.: Experimental Research on Mechanism of Transition. AGARD-Report #263, pg. 35 (1960)

Report describes experimental research on transition in an incompressible fluid in a smooth straight pipe. At constant delivery there is an intermittent state in which the flow is laminar at the inlet of the pipe and intermittent at the outlet, so-called turbulence spots preceded and followed by laminar flow. The inner transition in the pipe (with laminar inlet and turbulent outlet) occurs thru an intermittent and an incipient turbulent zone.

70. Mohorovicie, S.: Fundamental Formulas for Turbulent Motion in Fluids. Zeit. fur technische Physik, Vol. 6, 68-74 (1925)

New formulas for turbulent motion in fluids possessing internal friction are derived. These are applied to turbulence in circular pipe, and results are in almost complete agreement with observation. Transition states between turbulent and laminar motion can also be obtained on this theory. This work is all based on an equivalent viscosity.

71. Morgan, G. W., Ferrante, W. R.: Wave Propagation in Elastic Tubes Filled with Streaming Liquid. Jl. of the Acous. Soc. of Amer., Vol. 27, 715-725 (1955)

A theoretical analysis of the propagation of pressure waves thru elastic tubes filled with streaming incompressible viscous liquid is discussed. The analysis is restricted to tubes with thin walls and to liquids with sufficiently small viscosity. The steady-state motion of flow is approximated by Poiseuille flow.

72. Morgan, G. W., Kiely, J. P.: Wave Propagation in a Viscous Liquid Contained in a Flexible Tube. Jl. of the Acous. Soc. of Amer., Vol. 26, 323-328 (1954)

A theoretical analysis of the propagation of pressure waves thru liquid filled flexible tubes is presented. Expressions are derived which show the dependence of phase velocity and damping factor on the viscosity of the liquid and on internal damping in the wall.

73. Morkovin, M. V.: Transition from Laminar to Turbulent Shear Flow. ASME Trans., Vol. 80, 1121-1128 (1958)

Author reviews both theoretical and recent experimental work dealing with transition from laminar to turbulent shear flows.

*74. Narasimhan, M. N. L.: On the Steady Laminar Flow of Certain Non-Newtonian Liquids Through an Elastic Tube. Proc. Indian Acad. Sec. A., Vol. 43, 237-46 (1956)

A study of the effect of cross-viscosity on the radius of an elastic tube when certain highly viscous non-Newtonian liquids flow thru it under a pressure gradient.

*75. Nikuradse, J.: Untersuchungen über die Geschwindigkeitsverteilung in turbulenten Strömungen. Thesis Göttingen 1926. VDI - Forschungsheft 281, Berlin (1926)

*76. Nikuradse, J.: Turbulent Strömung in nicht Kre Ing. - Arch. 1, 306 (1930)

*77. Nikuradsc, J.: Gesetzmässigkeit der turbulenten Strömung in glatten Rohren. Forschungsheft 356 (1932)

*78. Orr, W. M. F.: Proc Royal Irish Acad., Vol. XXVII, 9-138 (1907)

79. Prandtl, L.: The Science of Phenomena of Flow. Zeits des Vereines deutcher Ingenieure, Vol. 73, 837 (1929)

Discussion is based largely on authors own work and work of his associates at Gottingen; particular attention paid to turbulent fluid motion; it can be said now that explanation of origin of turbulence has been found.

*80. Prandtl, L.: Bericht über neuere Untersuchungen über das Verhalten der laminaren Reibungsschicht ins besondere den laminar-turbulenten Umschlag. Mitteilungen Deutsche Akad. d. Luftfahrtforschung, Vol. 2 (1942)

81. Pröll, A.: Theory of Turbulent Currents in Tubes. Zeits, techn. Physik, Vol. 7, 428-434 (1926)

The investigations of Karman, Lorenz and Mohorovicie on the laws of turbulent motion are discussed. This paper also uses the assumption of an equivalent viscosity for turbulent motion.

82. Puryear, F. W.: Boundary Layer Control-Drag Reduction by use of Compliant Coatings. DTMB, Hydro. Lab. Research and Development Report #1668, 14 pg. (1962)

This report describes tests which were conducted on six models of identical size to determine whether a reduction in drag could be obtained by the use of compliant coatings to stabilize a laminar boundary layer.

*83. Reynolds, O.: Phil. Trans. Roy. Soc. (1883) or Collected Papers II, 51

84. Ritter, H.: Proposed Experiments on the Effects of Flexible Surfaces on Skin Friction. Admiralty Research Laboratory. A.R.L./NI/G/HY/9/7 (1960)

This note describes experiments to be made in the 30" water tunnel at A.R.L. for the purpose of investigating the effect on the boundary layer and hence on skin friction of flexible surfaces with internal damping, such as those described recently by Kramer.

85. Rothfus, R. R., Prengle, R. S.: Laminar - Turbulent Transition in Smooth Tubes. Indust. Eng. Chem., Vol. 44, 1683-88 (1952)

The transition flow of water in 2 tubes, with long calming sections, has been studied by means of dye injection. The Reynolds Number where transition occurs is determined.

86. Rotta, J.: Experimenteller Beitrag zür Entstehung turbulenter Strömung in Rohr. Ingenieur-Archiv., Vol. 24, p. 258 (1956)

This author measures the resistance to flow of air in pipes. He also measures the velocity fluctuation in the flow. As a result of his observation on the flow in the pipe, Rotte divides the boundary layer in transition into three different regions. In the first, the Tollmien-Schlichting waves are present. In the second the amplitude of the Tollmien-Schlichting waves is large enough to produce non-linear effects, random effects which characterize turbulent flow begins to appear. In the third phase these effects take on the general character of turbulent flow.

87. Rotta, J.: An Experimental Contribution to the Transition from Laminar to Turbulent Flow in a Pipe. 9th Congrès intern. Mécan. appl., Univ. Bruxelles, Vol. 3, 350-59 (1959)

This is a brief English exposition of the material given in previous paper by author in 1956*. The observation of intermittant burst of turbulence in a tube is an important contribution to the study of transition.

* See reference number 86.

88. Ryan, N. W., Johnson, M. M.: Transition from Laminar to Turbulent Flow in Pipes, A.I.Ch.E. Jl., Vol. 5, 433-35 (1959)

From intuitive arguments the authors developed mathematically a general criterion to characterize the flow regime in straight tubes of circular cross-section suitable for both Newtonian and non-Newtonian fluids.

89. Sackmann, L.: On the Transition Region of Flow Through Pipes. C.R. Acad. Sci., Paris, Vol. 226, 1343-45 (1948)

The author presents his experimental results on transition flow in pipes as a graph of mean velocity against the linear loss of head. These results show the effect of transition as a deviation from what could be expected for laminar flow. The results are as one would expect.

90. Sato, H., Kuriki, K.: Mechanism of Transition of Wake of Thin Flat Plate Placed Parallel to Uniform Flow. J. Fluid Mech., Vol. 11, 321-52 (1961)

Study of velocity fluctuations in laminar turbulent transition of boundary layer using modern techniques of hot wire anemometry in low turbulence wind tunnel. It has been possible to classify transition region into three sub-regions: 1) linear region, 2) non-linear region and 3) three-dimensional region.

91. Schiller, L.: Roughness and Critical Number; Experimental Contribution to the Turbulence Problem. Zeits. f. Physik, Vol. 3 412-416 (1920)

This article is concerned with the problem of transition. It concerns itself with determining whether some disturbance is necessary to initiate transition.

92. Schiller, L.: Experimental Investigations of Problem of Turbulence. Zeit. für angewandte Mathematik u. Mechanik, Vol. 1, 436-444 (1921)

This gives a systematic experimental description of the friction factor as a function of Reynolds Number. Transition is clearly indicated by the data. It is plotted on log-log paper and it shows the now familiar jump from one straight line to another at transition. The author finds the now familiar result that transition takes place at a different Reynolds Number when the speed is decreased or increased.

93. Schiller, L.: Turbulent Flow. Zeits. f. angew. Math. u. Mechanik, Vol. 14, 36-42 (1934)

This author describes his experiments in tubes in which he used dye injection at the leading edge to measure the initiation of turbulence and the resulting wave length in the disturbances. He reports good agreement between his simple theory of calculating the point of transition and the measured quantity.

94. Schlichting, H.: Background of Problems of Boundary Layer Research. AGARD Report #253, 34 pg. (1960)

The progress that has been made in the field of boundary layer research in recent years is briefly surveyed. The following items are treated to some extent: stability & transition, turbulent boundary layers, three-dimensional boundary layers, boundary layer control, boundary layers in hypersonic flow. In the concluding section, the unsolved boundary layer problems for incompressible flow are reviewed.

95. Schlichting, H.: Entwicklung der Grenzschichttheorie in den letzten drei Jahrzehnten. Zeit. für Flügwissenschaften, Vol. 8, 93-111 (1960)

Development of boundary layer theory during last 30 years; trends in development of fluid dynamics; transition from laminar to turbulent flow; control of boundary layer for achieving high lift and low drag on airfoil sections; aerodynamic heating at high Mach Number; effect of boundary layer on swept wings and rotating bodies.

96. Schlichting, H.: Boundary Layer Theory, 4th Ed. McGraw-Hill Book Company, Inc., New York (1960)

Introduces background of problems involved in motion of viscous fluids. Presents basic equations of boundary layer theory as derived from Navier-Stokes Eq. Theory is then extended to laminar and turbulent boundary layer with attention to problem of development of turbulence.

*97. Schlichting, H., Ulrich, A.: Zur Berechnung des Umschlages laminar/turbulent. Jahrb. der deutschen Luftfahrt-forschung, Pg. I8-35 (1942)

98. Schubauer, G. B.: Personal communication

99. Schubauer, G. B., Klebanoff, P. S.: Contributions to the Mechanics of Boundary Layer Transition. NACA Report #1289, 11 pg. (1956)

Using hot-wire techniques the authors investigated the transition range on flat plates. They found that: a) transition starts from perturbations in the laminar flow as spots which then grow in accordance with the general concept proposed by Emmons, b) turbulence always moves downstream followed by laminar flow and c) the following flow is in a state of calm for 2 periods during which transition will not occur.

100. Schubauer, G. B., Skramstad, H. K.: Laminar Boundary Layer Oscillations and Stability of Laminar Flow. J. Aero. Sci., Vol. 14, 69-78 (1947)

An account is given of an experimental investigation conducted at the Natural Bureau of Standards in 1940 and 1941, in which sinusoidal velocity fluctuations were studied in detail and found to agree with the characteristics predicted earlier by the Tollmien-Schlichting stability theory.

Includes in addition a comparison with certain of C. C. Lin's results.

101. Schubauer, G. B., Skramstad, H. K.: Laminar Boundary-Layer Oscillations and Transition on a Flat Plate. J. Res., Nat. Bur. of Stands., Vol. 38, 251-292 (1947)

This paper reports an investigation in which oscillations were discovered in the laminar boundary layer along a flat plate. These oscillations were found during the course of an experiment in which transition from laminar to turbulent flow was being studied on the plate, as the turbulence in the wind stream was being reduced to unusually low values by means of damping screens.

102. Sewell, K. G.: New Analytical Model for Boundary Layer Transition. Heat Transf. & Fluid Mech. Inst., Proceedings, 106-119 (1960)

Author presents new analytical model to describe transition on flat plate. Disturbance is assumed to oscillate both with time and position, to be amplified modulated with time and amplified exponentially with distance travelled.

103. Shen, S. F.: Calculated Amplified Oscillations in Plane Poiseuille and Blasins Flows. J. of Aero. Sci., Vol. 21, 62-64 (1954)

Shen supports Lin's and Heisenberg's calculation of hydrodynamic stability as opposed to that of Tollmien-Schlichting. Points out however that he has very little experimental data to support his opinion.

104. Smith, A. M. O.: Remarks on Transition in Round Tube. J. Fluid Mech., Vol. 7, 565-76 (1960)

Available theoretical and experimental knowledge concerning flow in inlet region of smooth round tube is analyzed; it is pointed out that e^9 amplification factor method predicts natural transition correctly over significant fraction of entire inlet length of tube; this indicates that flow becomes turbulent at higher Reynolds number because transition occurs in inlet length; results are applicable to both plane and axially symmetric flows.

105. Smith, L. L.: An Experiment on Turbulent Flow in a Pipe with a Flexible Wall. ASTIA AD 294-721, 37 pg. (1963)

The results of an experimental investigation of the effects of a flexible boundary on pressure drop in turbulent flow in a pipe are reported.

106. Tokita, N., Boggs, F. W.: Theoretical Study of Compliant Coatings to Achieve Drag Reduction on Underwater Vehicles. Final Report, Navy Contract Nonr-3120(00), Task NR 062-241, Mar. 1962

107. Tollmien, W.: Ein allgemeines Kriterium der Instabilitat laminarer Geschwindigkeitsverteilungen. NACA TM #792 (1936)

Presents authors detailed mathematical treatment for the stability of a laminar boundary layer when acted upon by infinitesimal disturbances.

108. Tollmien, W.: Aspekte der Stroemungs phsik. Zeit. fuer Flugwissenschaften, Vol. 10, 403-13 (1962)

The author gives a brief discussion of the Lighthill and Philips theories of noise generation by flow as well as a very brief discussion of cavitation, its causes and factors which influence it. This article is an excellent summary of the present state of the science of flow along boundaries.

109. Viguier, G.: The Transition in the Flow of Incompressible Fluid Along a Plane. Bull. Acad. Roy. Belgique Cl. Sci., Vol. 38, 1055-9 (1952)

The equations governing velocities in the transition zone from laminar to viscous flow of incompressible flow along a plane is established. In the discussion he uses a term in the third power of the shear stress for the constitutive equation. He finds a minimum when he calculates the drag coefficient as a function of Reynolds Number.

110. Weske, J. R., Plantholt, A. H.: Discrete Vortex Systems in the Transition Range of Fully Developed Flow in a Pipe. Jl. of Aero. Sci., Vol. 20, 717-19 (1953)

Authors examine details of process by which the original unidirectional vorticity of laminar flow is augmented and transformed to create the omnidirectional vorticity distribution encountered in turbulent flow. They give an expression which describes the process of conversion of energy of meansmotion of flow into energy of motion of discrete vortex filaments.

111. von Winkle, W. A.: Evaluation of a Boundary Layer Stabilization Coating. U.S. L. Tech. Memo, #922-111-61, May 15, 1961

112. Zondek, T.: Stability of Limiting Case of Plane Couette Flow. Phys. Rev., Vol. 90, 738-43 (1953)

Mathematical investigation of the stability of viscous incompressible couette flow is given by the method of small vibrations. The limiting case where the moving boundary is at infinity was treated. Shown that all modes of vibration are damped.

*113. Zyssina-Molozhen, L. M.: The Nature of the Transition from Laminar to Turbulent Flow in the Boundary Layer. Zh. tekh. fiz., Vol. 24, 1280-87 (1955)

An attempt is made to develop a semi-empirical method for evaluating the influence of the transitional region on the flow in the boundary layer.

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LITERATURE SEARCH INTO METHODS OF DAMPING OUT INCIPIENT TURBULENCE IN THE FLOW OF LIQUIDS - J. Thompsen, F.W. Boggs, N. Tokita
Final Report, Jan. 9, 1964, Contract DA-30-069-AMC-287(T), OMS 5011.11.83800.01, PRON No. EH-1R563-01-EH-AC

1. Fluid flow, Transition
2. Contract DA-30-069-AMC-287(T)

This report presents a bibliography of articles, with abstracts, concerning the problem of transition from laminar to turbulent flow over flat plates and thru pipes. These articles deal with theories used to describe (1) the mechanism of transition and (2) the means to delay it, in order to reduce drag or flow noise of fully submerged bodies.

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Final Report, Jan. 9, 1964, Contract DA-30-069-AMC-287(T), OMS 5011.11.83800.01, PRON No. EH-1R563-01-EH-AC

1. Fluid flow, Transition
2. Contract DA-30-069-AMC-287(T)

This report presents a bibliography of articles, with abstracts, concerning the problem of transition from laminar to turbulent flow over flat plates and thru pipes. These articles deal with theories used to describe (1) the mechanism of transition and (2) the means to delay it, in order to reduce drag or flow noise of fully submerged bodies.

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